

Heat driven thermoacoustic cooler based on traveling–standing wave

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ABSTRACT

This paper presents a heat driven thermoacoustic cooler system without any moving part. It consists of a thermoacoustic engine and a thermoacoustic cooler, and the former is the driving source of the latter. Both the engine and the cooler are located in one loop tube coupled with a resonator tube, and the acoustic power produced by the engine is used to drive the cooler directly. Both regenerators of the engine and the cooler are located in the near region of the pressure antinode, and operate in traveling–standing wave phase region. In the engine's regenerator, both components of the standing wave and the traveling wave realize the conversion from heat to acoustic energy. This improves the efficiency of the engine. In the cooler's regenerator, both components of the traveling wave and the standing wave pump heat from the cold end. This improves the efficiency of the cooler. At the operating point with a mean pressure of 22 bar, helium as working gas, a frequency of 234 Hz, and a heating power of 300 W, the experimental cooler provides a no-load temperature of $-30\text{ }^{\circ}\text{C}$ and a cooling power of 40 W at the cooling temperature of $0\text{ }^{\circ}\text{C}$. The total length of this cooler system is less than 1 m, which shows a good prospect for the domestic cooler system in room-temperature cooling such as food refrigeration and air-conditioning.

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1. Introduction

The thermoacoustic engine (TAE) converts heat to acoustic energy by the thermoacoustic principles. The acoustic energy produced by the TAE can be used to drive the thermoacoustic cooler (TAC). The system combining the TAE and TAC is called a heat driven thermoacoustic cooler system [1,2]. In the heat driven thermoacoustic cooler system, when a steep temperature gradient is set up along the regenerator, the acoustic wave with the oscillating pressure $p_1 = |p_1|e^{i(\omega t + \varphi_z)}$ and the oscillating velocity $u_1 = |u_1|e^{i\omega t}$ is excited, where ω is the angular frequency and φ_z is the leading phase of p_1 to u_1 . When the acoustic wave passes through the TAC's regenerator, a temperature gradient along the TAC's regenerator with a certain coefficient of performance (COP) is set up. The acoustic wave drives gas parcels in the thermoacoustic regenerators to experience a certain thermodynamic cycle. Then, the conversion from heat to acoustic energy and the heat pumping occur without any moving parts in the system. Compared with traditional heat devices, the heat driven thermoacoustic cooler system has three main advantages: (1) it has simple structure, no moving parts, low cost of manufacture, and high reliability; (2) by using inert gases as working fluid, this kind of machines is environmentally friendly; (3) the thermoacoustic devices can be driven by low

quality energy source such as exhausting thermal energy and solar energy, so it is significant for remote rural areas where electricity is scarce.

The research on the heat driven thermoacoustic cooler system has progressed steadily over decades, and profited greatly from the publication of thermoacoustic theory. In the early time, the heat driven thermoacoustic cooler is heat driven orifice pulse tube coolers [3,4] which used the TAE instead of the compressor. These inventions are effective cryocooler apparatus without any moving part. However, the orifice pulse tube cooler is efficient only in the cryogenic temperature region and is inherently inefficient for small temperature spans. For the orifice pulse tube cooler, the cooling power is comparable in magnitude to the mechanical power dissipated as heat due to the orifice. For cryogenic coolers, the Carnot COP is very small, so the energy wasted by the orifice is almost negligible and less important than other factors. For a small temperature span cooler (e.g. an air conditioner), the orifice pulse tube cooler would have a COP less than unity. And a heat driven cooler would have a total efficiency defined as the ratio of the cooling power to the heating power very much less than unity.

Subsequently, research on heat driven thermoacoustic cooler with small temperature span has drawn many attentions [5]. Because the match between varied TAE and TAC has great influence on the efficiency, many researchers have paid particular attention to the cascade thermoacoustic device with compact structure. In 1989 [1], a heat driven thermoacoustic cooler was designed by Wheatley et al. Although the cooler was simple and had no moving

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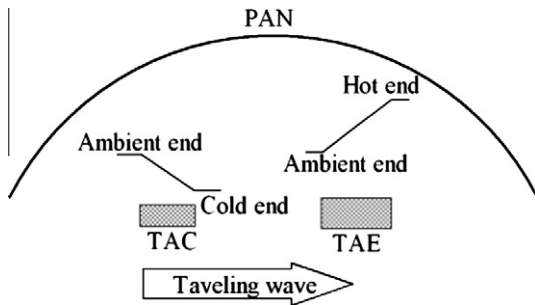


Fig. 1. The regenerators arrangement of the thermoacoustic system described in Ref. [8].

parts, it had a very poor total efficiency in the range of 0.05–0.1 for a modest cooling temperature span. The reason of the low efficiency is that most of the standing wave component (TWC) propagates in opposite direction of the temperature gradient in the TAE's regenerator, which results in that the TWC consumes acoustic energy [6]. This substantially decreases the efficiency of the engine. In 1997, Hofler [7] enhanced the efficiency of the engine by adjusting the contribution of the TWC in this type of device. However, the regenerators of that device mainly worked in the standing wave mode whose thermoacoustic conversion was based on an intrinsically irreversible thermodynamic cycle. In 2002, Ueda et al. [8] studied a system of two regenerators in one loop tube and pointed out that the reversible functions of both the TAE and the TAC was realized. In such heat driven thermoacoustic cooler system, the TAC was located above the TAE. The cold end of the TAC's regenerator was close to the pressure antinode (PAN), and the ambient end of the TAE's regenerator was close to the PAN. As the description of Ref. [8], the arrangement of the regenerators can be obtained as shown in Fig. 1. For the cooler's regenerator, the TWC pumps heat from cold end to hot end [6], while the standing wave component (SWC) transports heat from hot end to cold end [9]. This degrades the efficiency of the TAC. For the TAE's regenerator, the TWC propagates from cold end to hot end to amplify the acoustic power [6], while the SWC consumes acoustic energy [9]. This substantially decreases the efficiency of the TAE.

For improving the thermoacoustic efficiency, this paper will introduce a heat driven thermoacoustic cooler by adjusting the contributions of the TWC and the SWC. Although the two regenerators of the system introduced in this paper are also located in one loop tube coupled with a resonator tube, the TAC is located below

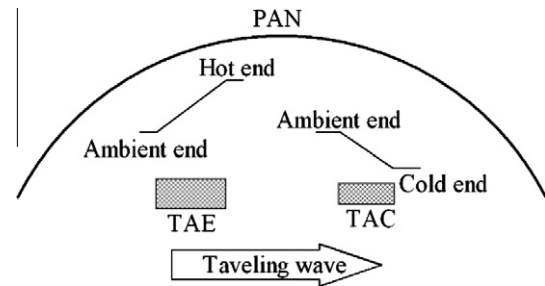


Fig. 3. The regenerators arrangement of the thermoacoustic system described in this paper.

the TAE, as shown in Fig. 2. By designing these thermodynamic components carefully, it is possible to make the PAN in the center of the thermal buffer tube (TBT) between the TAE and the TAC, and the direction of the acoustic power flow in the loop tube is anti-clockwise. This makes the arrangement of the regenerators be same as Fig. 3. For the cooler's regenerator, both the TWC and the SWC pump heat from the cold end, which improves the COP of the TAC [6,9]. For the engine's regenerator, both the SWC and the TWC realize the conversion from heat to acoustic energy [6,9], which improves the efficiency of the TAE.

2. Simulation of the thermoacoustic device

Although there are many computation software of thermoacoustics (e.g. Design Simulation for ThermoAcoustic Research (DSTAR) [10], REGEN3 [11], and Design Environment for Low-amplitude ThermoAcoustic Energy Conversion (DeltaEC) [12]), just DeltaEC can be used to calculate a variety of complicated thermoacoustic device with low-amplitude pressure. The calculation capability and precision of the thermoacoustic devices has been validated by many research [13,14]. DeltaEC written by Los Alamos laboratory solves the one-dimensional wave equation based on the usual low-amplitude, acoustic approximation. It solves the wave equation in a gas or liquid, in a geometry given by the user as a sequence of segments, such as ducts, compliances, transducers, and thermoacoustic stacks or regenerators. A solution to the appropriate 1-d wave equation is found for each segment, with pressures and volume flow rates matched at the junctions between segments. In stacks, the wave equation solution is found simultaneously with that of the energy-flow equation in order to find

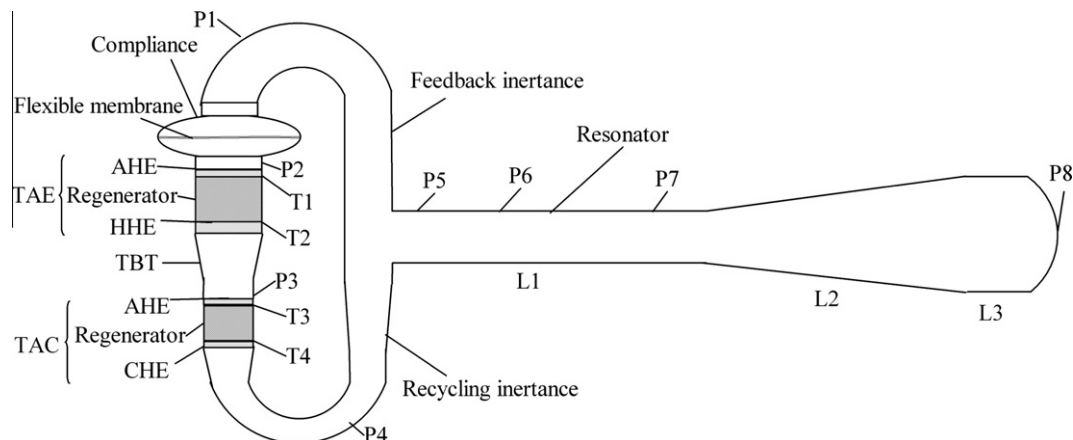


Fig. 2. The schematic of the heat driven thermoacoustic cooler and the measurement set up. Where AHE is the ambient heat exchanger; HHE is the hot heat exchanger; CHE is the cold heat exchanger; and TBT is the thermal buffer tube. Eleven calibrated pressure sensors, labeled P1–P8, and four calibrated NiCr–NiSi thermocouples, labeled T1, T2, T3 and T4, are arranged in the system.

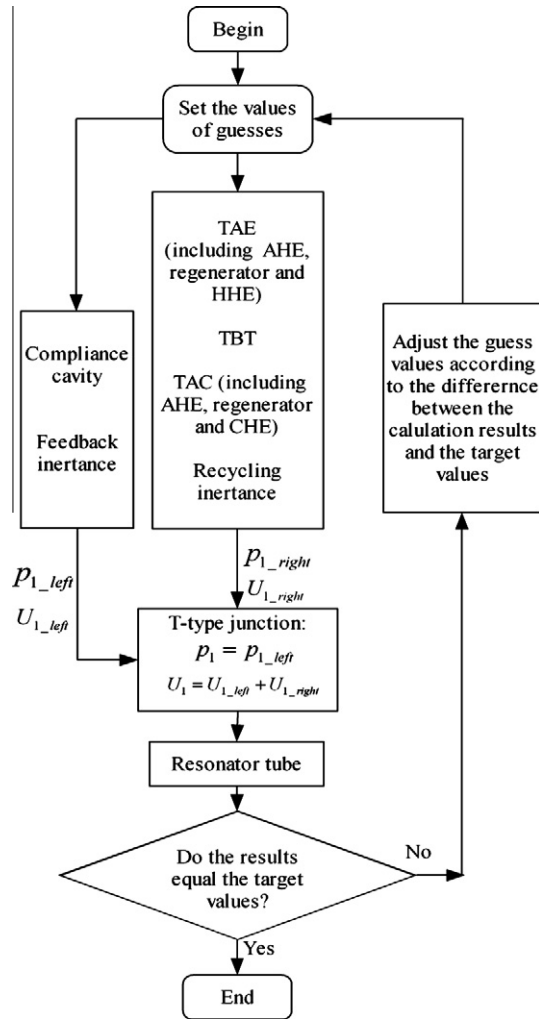


Fig. 4. The flowchart of the simulation for the heat driven thermoacoustic cooler.

the temperature profile as well as the acoustic pressure. The energy flow through stacks is determined by temperatures and/or heat flows at adjacent heat exchangers.

According to our problem, this paper selected DeltaEC to simulate the acoustic field and the acoustic power flow in the thermoacoustic device. An x -coordinate is set up for convenient analysis of calculations and analyses in this thermoacoustic system. Here, the top of the ambient heat exchanger (AHE) of the TAE is set as the origin of the coordinate ($x = 0.0$ m). The negative direction of x is taken clockwise from the top of the TAE's AHE, through the compliance cavity and the feedback inertance, to the T-type junction where $x = -0.31$ m. The positive direction of x also starts from the top of the TAE's AHE, propagating down through the TAE, TBT, TAC, and recycling inertance, to the T-type junction where $x = 0.52$ m, and then turns right through the resonator to the end of the cavity where $x = 1.40$ m.

The simulation for the thermoacoustic device is from the origin along the established coordinate to each segment, with pressures and volumetric velocities matched at the junctions between segments. The simulation order is shown in Fig. 4. The simulation starts near the top of AHE of TAE, shown in Fig. 1. It integrates up, right, and down, through the compliance and feedback inertance to the junction. It then starts again just above the AHE of TAE, going down through the TAE, TBT, TAC, and reclaiming inertance to reach the junction a second time. The complex p_1 at the

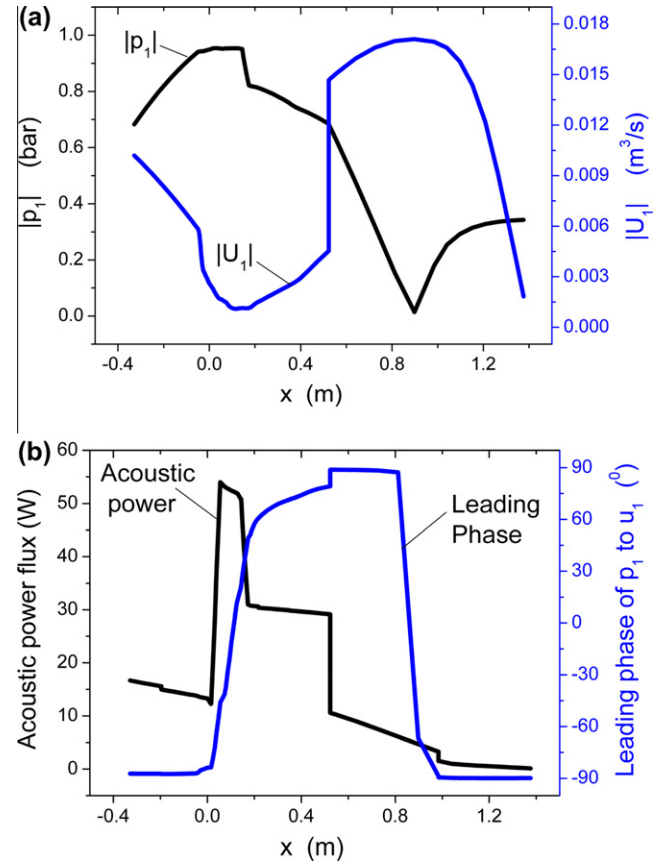


Fig. 5. The distributions of the pressure amplitude $|p_1|$, the volume-velocity amplitude $|U_1|$, the leading phase φ_z of the oscillating pressure to the oscillating velocity, and the acoustic work flow in the thermoacoustic system.

T-type junction must match up, which is one of boundary condition. The integration then proceeds through the resonator to the end cap, where the boundary condition is $U_1 = 0$. A shooting method is used in the integration.

For the typical operating condition (a mean pressure of 22 bar, a HHE's temperature of 560 °C, and a CHE's temperature of 0 °C), the calculation results of the distributions of the acoustic power flow and the acoustic field in the system are shown in Fig. 5.

Fig. 5a shows the axial distribution of the pressure amplitude $|p_1|$ and the volume-velocity amplitude $|U_1|$. The pressure amplitude reaches the maximum at the TAE and then decreases sharply in the regenerator of TAC. At $x = 0.85$ m, the pressure amplitude becomes minimums, which is the pressure node. The minimum velocity in the looped tube of the system appears near the location of $x = 0.115$ m between the TAE and the TAC. That the velocity amplitude approaches to zero near the regenerators will contribute to reducing the viscous loss in the regenerator, which is helpful for improving the efficiency of the regenerators. In addition, there is an abrupt point in Fig. 5a. In fact, the abrupt point of $x = 0.54$ m is at the T-type junction where the sum of the velocity of the feedback inertance and the velocity of the recycling inertance will act as the velocity at the entrance of the resonator. So the velocity at the T-type junction is not continuous and in the resonator could be larger than the velocity in the looped tube. It means that much acoustic power will dissipate in the resonator. It is found that the maximum of the pressure amplitude and the minimum of the velocity amplitude appear close to the regenerators. Therefore, the specific acoustic impedance Z would reach the maximum near the regenerator, and the viscous loss in the regenerators can be well reduced.

Fig. 5b presents the distribution of the acoustic power flow and the leading phase φ_z of the oscillating pressure relative to the oscillating velocity. φ_z increases gradually from the T-type junction ($x = -0.31$ m), and becomes a traveling wave phase at $x = 0.115$ m, between the TAE and the TAC. The TAE's regenerator works in the region of $-75^\circ < \varphi_z < -45^\circ$, and the TAC's regenerator works in the region of $20^\circ < \varphi_z < 50^\circ$. It is indicated that the regenerator of TAE realized the conversion from heat to acoustic energy by both the SWC and the TWC, and that the TAC's regenerator pumps heat from the cold end by both the SWC and the TWC. The total efficiency of the thermoacoustic device can be improved. On the other hand, from Fig. 5b, the leading phase φ_z in the resonator is 90° at first, and then it drops to -90° after the pressure node ($x = 0.85$ m).

According to Fig. 5b, the acoustic power of 12.3 W enters the ambient end of the TAE's regenerator and increases along the regenerator with a positive temperature gradient established by externally inputting heat through the hot heat exchanger (HHE). Then, an acoustic power of 54.0 W is gained at the hot end of the TAE's regenerator. These calculation data show that the TAE can produce a net acoustic power of about 41.7 W at an input heat power of 154 W, corresponding to a thermoacoustic conversion efficiency of 27.3%. After being slightly dissipated in the TBT, the acoustic power of 50.8 W enters the ambient end of the TAC's regenerator, and is used to pump heat directly. It is reduced gradually due to the consumption of acoustic power for pumping heat from the cold end of the regenerator. When it comes out of the CHE with a value of 30.8 W, the acoustic power consumed by the TAC is 20 W. The net cooling power of the TAC given by the calculation is about 48 W. It implies that the TAC achieves a COP of about 2.4 at the cooling temperature of 0°C . The 27.3 W residual acoustic power, after being slightly dissipated in the recycling inductance tube, is divided into two branches at the T junction: one branch of 10.6 W propagates into the resonance tube and is dissipated in the resonance tube; the other branch of 16.7 W slightly dissipated through the feedback inductance enters the TAE again. These calculation results show that the total efficiency of the device reaches 31.2% at the cooling temperature of 0°C .

3. Experimental system

The thermoacoustic device studied here is a heat driven thermoacoustic cooler as shown in Fig. 2. It is composed of a torus-shaped section and a resonator tube. A description of the each parts of the system is given in the following.

The resonator tube includes a straight pipe with an inner diameter of 22 mm, a taper tube, and a cavity with an inner diameter of 80 mm. The lengths L_1 , L_2 and L_3 of the resonator tube are 0.46 m, 0.28 m and 0.14 m respectively.

The torus-shaped section contains a feedback inductance, a compliance cavity, a flexible membrane, a TAE (including an AHE, a regenerator and a HHE), a TBT, a TAC (including an AHE, a regenerator and a CHE), and a recycling inductance.

Near the top of the torus is the compliance cavity with an inner diameter $d = 0.1$ m and volume $V = 6.5 \times 10^{-4} \text{ m}^3$. The flexible membrane was inserted into the middle of the cavity to suppress the circulating second-order mass flow, called as "Gedeon streaming" [15,16]. The flexible membrane is made of silica gel with a thickness of 0.5 mm. The larger cross-sectional area of the cavity achieves two benefits compared with a constant diameter tube: (1) the length of the cavity can be reduced for a given frequency, which makes the device more compact [17]; (2) the acoustic power dissipated due to the flexible membrane can greatly decrease because of the reduced oscillating velocity.

Below the cavity is the TAE with a consistent inner diameter of 27 mm. The TAE's regenerator is sandwiched between the AHE and

the HHE, as shown in Fig. 2. The 40 mm long regenerator is made of 60-mesh stainless-steel screens with a wire diameter of 0.12 mm. The 15 mm long AHE is a parallel plate-type heat exchanger, with working gas oscillating in the spaces between plates, and ambient-temperature water flowing in the round jacket spaces surrounding the fins. The 18 mm long HHE consists of ceramic honeycombs in which the long electric heating filament is wound.

The TBT between the TAE and the TAC consists of a 37 mm long taper tube and a 16 mm long tube. The taper tube is used to connect the TAE and the TAC via its reducing diameter. The taper angle is designed to suppress Rayleigh streaming [18].

The TAC with a consistent inner diameter of 22 mm is located below the TAE. The TAC's regenerator is sandwiched between the AHE and the CHE, as shown in Fig. 2. The 34 mm long regenerator is made of 150-mesh stainless-steel screens with a wire diameter of 0.12 mm. The 15 mm long AHE is also a parallel plate-type heat exchanger. The 12 mm long CHE consisting of 80-mesh copper screens is heated by electrical resistance heater wound around it.

The recycling inductance is used to recycle the residual acoustic power out of the TAC. It consists of a 40 mm long taper tube, a 180° bend tube with an inner diameter of 16 mm and length of 120 mm, a 114 mm long taper tube, and a 46 mm long tube with an inner diameter of 22 mm. The 278 mm long feedback inductance with an inner diameter of 22 mm is used to transfer part of the recycle acoustic power to the TAE, and then the acoustic power is amplified again.

The compact acoustic network consists of resistances of the regenerator units, TBT, compliance cavity, feedback inductance, and recycling inductance. It is used to create the local traveling-standing wave phase and the high specific acoustic impedance in the regenerators. By designing these thermodynamic components carefully, it is possible to make the PAN in the center of the TBT between the TAE and the TAC, and the direction of the acoustic power flow in the loop tube is anti-clockwise. This makes the arrangement of the regenerators be the same as Fig. 3.

In experiments, the pressure data have been acquired and analysed without time delay by a computer. As shown in Fig. 2, eight calibrated pressure sensors, labeled P1–P8, are arranged in the system: pressure sensor labeled P1 is located at the feedback inductance tube; P2 is located at the top of the TAE's AHE; P3 is located at the TBT between the two stages; P4 is located at the recycling inductance tube; P5 is located at nearby the T-type junction; P6, P7 and P8 are located along the resonance tubes in order to obtain the distribution of the acoustic field in the cooler system. The pressure data acquisition system is comprised of the pressure sensors, a data acquisition board, a computer with the data acquisition program developed by us. The pressure sensors are the piezoelectric type (CY-YD 208), supplied by Sinocera Piezotronics, Inc., China. The data acquisition board is AC1810, 12 bits precision and 10 ks/s sampling frequency. The output voltage from the piezoelectric transducer is amplified by a charge amplifier and a signal amplifier, and then sent to the AC1810 board connected to the computer. Through running the data acquisition program, the pressure signal can be show on the screen of the computer. The phase of the pressure signal and operating frequency is measured by a Stanford Research model SR-830 DSP lock-in amplifier. Also four calibrated NiCr–NiSi thermocouples, labeled T1, T2, T3 and T4, are arranged in the system, as shown in Fig. 2. The thermocouples labeled T1 is located at the ambient end of the TAE's regenerator; T2 is located at the hot end of the TAE's regenerator; T3 is located at the ambient end of the TAC's regenerator; and T4 is located at the cold end of the TAC's regenerator. The temperature data are measured by calibrated NiCr–NiSi thermocouples (with $\pm 1^\circ\text{C}$ accuracy). The temperature signal can be acquired by the computer through a modern digital multi-purpose meter and its driver software, provided by the

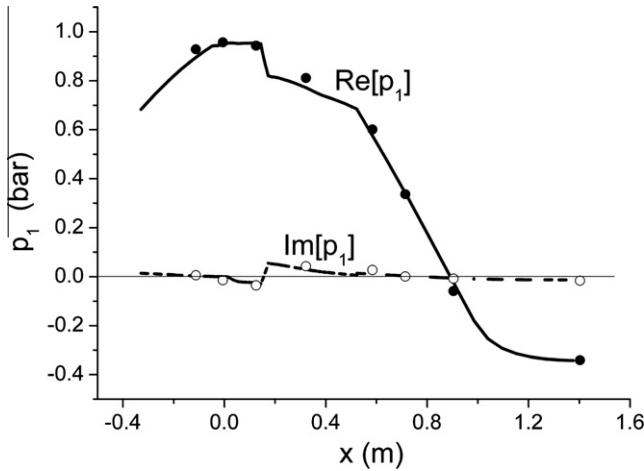


Fig. 6. $\text{Re}[p_1]$ and $\text{Im}[p_1]$ of the acoustic pressure for a operating point. Points are measured values, and lines are calculations.

UNI-T, Inc., Hong Kong. Heating power is regulated by changing the voltage.

4. Experimental results and discussion

To test practical performances of the whole system, a series of experiments have been done. During the preliminary experiments, the hot end temperature of the TAE's regenerator was mostly kept around 650 °C or below. The heat was input into the HHE of the TAE and an acoustic oscillation starts spontaneously when the temperature inside the HHE rises above a critical value.

We present firstly the agreement between the measured and calculated in order to yield confidence in the calculation, and together $\text{Re}[p_1]$ and $\text{Im}[p_1]$ of the acoustic pressure form the basis for trying to understand the velocity, the leading phase φ_z , and the powers in the device. Fig. 6 shows $\text{Re}[p_1]$ and $\text{Im}[p_1]$ of the acoustic pressure under the condition of a mean pressure of 22 bar, helium as working gas, a HHE's temperature of 560 °C, and a CHE's temperature of 0 °C. The disagreements between measured and calculated complex pressures in Fig. 6 are typically 3%, and at most 7%. The operating frequency of 234 Hz was measured by a Stanford Research model SR-830 DSP lock-in amplifier. The disagreement between the measured frequency of 234 Hz and calculated frequency of 235 Hz is about 0.5%.

Fig. 7 gives the experimental curve of cooling powers under different mean pressures and heating powers. It can be seen that the cold end temperature T_{cold} varies with the cooling power. According to Ref. [7], in the cascade thermoacoustic system, the temperature of regenerators will influence the position of the PAN, and then will influence the thermoacoustic conversion efficiency. Thus, T_{cold} as a function of Q_2 derives from the linear behavior, as shown in Fig. 7.

Particularly, under the condition of the mean pressure of 22 bar, helium as working gas, frequency of 234 Hz in the experiment and circulating water temperature of 16 °C, the cooler provides the lowest temperature of −30 °C with a heating power of 300 W. At the same operating condition, the cooler can provide a cooling power of 40 W at the cooling temperature of 0 °C. Compared with the experimental results, the calculations predicted an overall performance of 31%, while the measurements show a performance of only 13% at 0 °C. The reason of such behavior is that the calculation based on DeltaEC

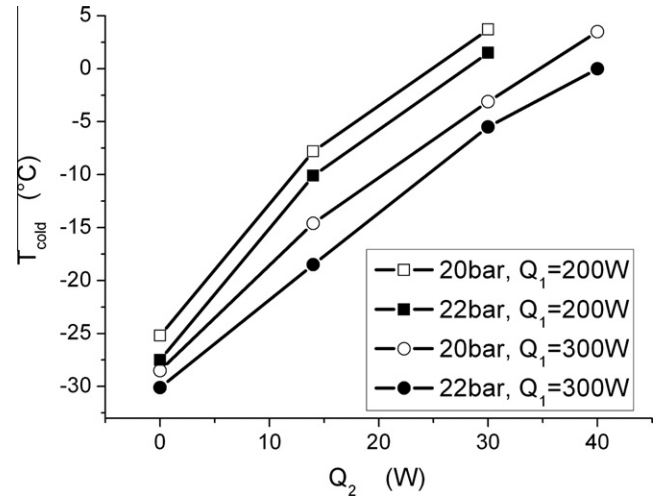


Fig. 7. The cooling temperature T_{cold} with different heating power Q_1 and cooling power Q_2 .

does not consider the heat leak. The heating power and the cooling power in the calculations are the heat related to the thermoacoustic processes. However, the heating power and the cooling power, measured by a commercial wattmeter, does include the heat leaks through the metal of the regenerator screen bed, through the surrounding pressure-vessel wall, through the TBT wall, through the ceramic fiber insulation surrounding the TBT and regenerators, and as well as the thermal radiation to the environment.

5. Conclusions

This paper proposed a new configuration of the heat driven thermoacoustic cooler. Based on new configuration idea and the analysis results, a miniature scale heat driven thermoacoustic cooler has been designed, manufactured and tested. Compared with the existed types of the heat driven thermoacoustic coolers, this device has the merits: (1) it utilizes synthetically the thermoacoustic performance contributed by both of the traveling wave component and the standing wave component; (2) the acoustic power produced by the engine is used to drive the cooler directly; (3) the feedback tube realizes the recycle of the residual acoustic power out of the cooler.

Calculations and experiments show a good agreement, such as frequency and pressure. According to the analyses and experiments, the leading phase of oscillating pressure to oscillating velocity in the regenerator of TAE is located in the region of $-75^\circ < \varphi_z < -45^\circ$, and the hot end is close to the PAN. The leading phase in the regenerator of TAC is located in the region of $20^\circ < \varphi_z < 50^\circ$, and the ambient end is close to the PAN. Both the SWC and the TWC realize the conversion from heat to acoustic energy in the TAE's regenerator and pumping heat from the cold end in the TAC's regenerator, which increases the efficiency of the system. At the operating point with the mean pressure of 22 bar, helium as working gas, frequency of 234 Hz, and a heating power of 300 W, the experimental cooler provides a no-load temperature of −30 °C and a cooling power of 40 W at the cooling temperature of 0 °C.

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